REMR Technical Note CS-ES-1.11

Interim Fracture and Fatigue Analysis for Aging Steel Miter Gates

Purpose

To provide interim fracture and fatigue analysis criteria for aging steel miter gates. This technical note covers the inspection procedures, laboratory tests, and interim fatigue and fracture criteria.

Inspection Procedures

Corps criteria require miter gates to be visually inspected every 5 years by a team of design engineers (ER 1110-2-100). However, this and other existing Corps criteria do not specifically address inspection for possible fracture. Specific criteria are needed for inspecting the critical members of miter gates and their connections. Critical members are defined as those structural elements that, should they fail, would render the gate inoperable. Areas that should receive special attention during the inspection include, but are not limited to (a) weldments, (b) details that are particularly susceptible to fatigue, and (c) corroded areas. If distressed gate members or connections are identified, a detailed nondestructive examination (NDE) should be performed at a later date. Recommended NDE methods include visual, liquid penetrant, magnetic particle, or ultrasonic examinations. Table 1 shows the applicable ASTM standards for NDE testing.

Table 1
Types of Nondestructive Tests

Test	Applications	Applicable ASTM Standards
Liquid penetrant	Surface discontinuities	E165
Magnetic particle	Surface discontinuities and large subsurface voids	E709
Ultrasonic	Most discontinuities	E114 and E164

Laboratory Tests

Miter gate structural members are constructed of structural grade carbon steel. The structural steel used for gates constructed prior to about 1965 was most likely steel that met ASTM A7 (although ASTM A9, A94, and A140 may also have been used), while the steel used for miter gates constructed after that time was primarily steel meeting ASTM A36, Specification for Structural Steel, and in some cases higher strength steels, such as ASTM A472, Specification for High-Strength, Low-Alloy Columbium-Vanadium Steels of Structural Quality. If the steel chemistry, tensile properties, ductility, and fracture toughness properties are known, physical specimens will not be needed. However, on many gates, these data are not available, and it may be required to remove base material and/or weld test specimens to fabricate coupons for testing in the laboratory. When the tests are required to determine the mechanical properties for a fracture or fatigue analysis, the ASTM tests considered are given in Table 2.

Table 2
Material Testing

Test	Purpose	Applicable ASTM Standard
Chemical analysis	To assess corrosion problems and material weldability	E350
Tension	To determine the tensile properties, Young's Modulus, and stress-strain curve	E8
Charpy V-Notch	To determine the toughness value	E23
Crack tip opening displacement	To determine the fracture incipient load	E1290

Fracture Mechanics

Fracture mechanics has shown that fracture toughness, crack size and stress are the primary factors that determine the susceptibility of steel to fracture. Other contributing factors are service temperature, constraint, loading rate, cold working of the steel, and residual stresses. Brittle fractures may be analyzed using linear elastic fracture mechanics (LEFM) principles, while ductile fractures are analyzed using elastic-plastic fracture mechanics (EPFM) principles.

The basic principle of LEFM is that incipient unstable crack growth will occur when the stress intensity factor K_I equals or exceeds the critical stress intensity factor K_c. However, in many applications, there is extensive plastic deformation prior to a crack, causing failure of the member. For more extensive plastic deformation, the stress intensity factor approach is no longer valid, so several EPFM methods have been developed (J-Integral, R-Curve, and crack-tip opening displacement (CTOD)). The CTOD approach has been extensively applied to the analysis of cracks in welded steel structures and is the EPFM approach in the recommended guidance.

Fracture may occur if a member is subjected to cyclic loading that causes fatigue cracks to propagate to critical size. Fatigue crack initiation almost always occurs at a point of stress concentration, and the cracks propagate as a result of the cyclic stresses. When evaluating fracture of critical members that are subjected to fatigue loads, the following areas are particularly susceptible to crack growth:

a. Details that produce severe stress concentrations such as abrupt section changes, re-entrant corners, and notchlike corners.

b. Abrupt changes of section or stiffness in members or components.

c. Alignment of parts that cause eccentricities.

d. Intersection of and intermittent welds in tension members.

e. Connections where rivets were poorly installed, high-strength bolts were not adequately clamping the connection together, and welds are unsound.

Recommended Interim Fracture and Fatigue Analysis Criteria

Recommended fracture analysis criteria are divided into three cases: linear elastic, transition, and elastic-plastic cases.

a. *Linear elastic case*.: The ASTM E399 requirement for plane-strain condition can be expressed in terms of Irwin's (1964) plane-strain β_{Ic}. If $\beta_{Ic} < 0.4$, LEFM can be applied. K_{Ic} is determined from Charpy V-Notch toughness data using the Barson/Rolfe (1987) two-stage transition (determining K_c by testing in accordance with ASTM E399 is permitted but not usually practical for mild structural steels). The critical crack size is determined by equations developed by Tada, Paris, and Irwin (1985). If the actual crack size is less than the critical crack size including a factor of safety, the crack is allowable (a factor of safety of 2 is recommended for the allowable crack size). However, any observed cracks should be monitored and re-evaluated if any crack propagation occurs.

b. *Transition case*. This case applies to situations where plane strain conditions are violated and the applied stress (nominal + residual + geometric effects excluding effect of crack tip) at the location under consideration is less than the yield stress. The toughness value used is K_c, which is a toughness parameter based on thickness. The same criterion as Case *a* is applicable to determine the allowable crack size.

c. *Elastic-plastic case*. This case applies to situations where the applied stress (including nominal residual and geometric effects) is greater than the yield stress. The recommended approach to performing a CTOD analysis is that specified by the British Standards Institution (1979). Critical CTOD is determined in accordance with ASTM E1290 or BS 5762 (British Standards Institution 1979). If $\delta < \delta c$, the crack size is allowable.

Recommended fatigue analysis criteria for welded or riveted miter gate members are as follows:

a. *Welded members*. The crack initiation portion of life is not considered since welded structures include initial defects. A crack will not propagate if the stress intensity factor range value ΔK is less than the fatigue threshold stress intensity factor ΔK_{th}. Otherwise, Paris' Law (Barsom and Rolfe 1987) is applied to determine crack growth rate.

b. *Riveted members*. The fatigue life of riveted connections is determined by Category C or D detail, depending on the stress range under consideration. Category D AASHTO stress range versus the number of cycles (S_r - N) curve for welded details is used when $S_r \leq$ 10 kip per square inch (ksi) 69 megapascals (MPa)) and the Category C curve is used for s_r < 10 ksi (69 MPa).

References

Barsom, J.M., and Rolfe, S.T. (1987). *Fracture and fatigue control in structures*. 2nd Ed. Prentice-Hall.

British Standards Institution. (1979). "Methods for crack-tip opening displacement (CTOD) Testing," BS 5762.

______. (1980). "Guidance on some methods for the derivation of acceptance levels in fusion welded joints," PD 6493.

ER 1110-2-100. (1988). "Periodic inspection and continuing evaluation of completed civil works." Corps of Engineers Publication Depot, Hyattsville, MD.

Irwin, G.R. (1964). "Crack-toughness testing of strain-rate sensitive materials," *Journal of Engineering for Power*, Transactions of the ASME Series A, 86, 444.

Tada, H., Paris, P.C., and Irwin, G.R. (1985). *The stress analysis of cracks handbook*. Paris Productions, St. Louis.